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Circuit-Commutated Turn-Off Time of Thyristors

by U. Van Bogget

Thyristor turn-off time is one of the most difficult semiconductor parameters to determine because of its strong dependency on many variables, such as junction temperature, gate bias, and anode-voltage and anode-current waveforms. Because of this strong dependency, it makes no sense to specify the turn-off time of a thyristor without specifying precisely the conditions under which that time was determined. But it is impossible to choose a set of conditions that will match the interests of all present or potential purchasers of the device. Therefore, the need for a new concept for measuring the circuit commutated turn-off time of thyristors.

The turn-off-time measurement method described in this Note is very different from the conventional, complex turn-off-time specification mentioned above; it is a very basic method intended to measure the turn-off time as a simple parameter under conditions that are not critical for measurement precision and that can be easily reproduced by any thyristor user. Data are provided to assure correct interpretation of the new measurement, inherent turn-off time, T_{Qi}.

The basic inherent-turn-off time measurement circuit is shown in Fig. 1. When a

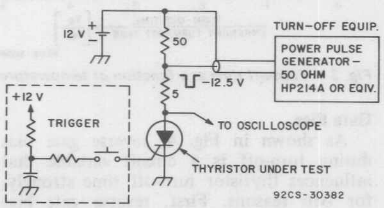

Fig. 1 – Basic inherent-turn-off time measurement circuit.

thyristor is turned on by gate current or any other means, anode current circulates; the value of the anode current depends on the anode supply voltage and internal impedance. The gate current may be interrupted, and the thyristor will stay in the on state as long as its anode current does not drop below a certain level called the "holding current" level. This phenomenon is the result of the injection of the anode emitter holes into the cathode emitter. The anode holes replace the gate holes that began the turn-on by initiating the injection of electrons from the cathode emitter into the anode emitter. The turn-on and on-state phenomena are shown in Figs. 2(a) and 2(b), respectively.

To switch the thyristor off from the on state, it is necessary to reduce the anode current to a lower level or to zero so that both anode and cathode emitters stop the injection of carriers. In the inherent turn-off-time measurement, this reduction of current is accomplished by means of a pulse generator, which allows good control of the circuit turn-off time.

When the injection of carriers is stopped, minority carriers are still present in both p and n bases. Some of these carriers return to their respective emitters (they constitute the recovery current) and some recombine within the bases. When the recovery and recombination phenomena are complete, voltage can be applied again between anode and cathode without turning the thyristor on.

It is obvious that the anode voltage can be reapplied before completion of recombination because at a certain time the remaining minority carrier density in the bases is so low that they can no longer initiate the regenerative injection required between anode and cathode emitters to turn the device on. The critical time after current interruption at which anode voltage can be reapplied without turning the device on again depends mainly on such parameters as recombination velocity or minority-carrier lifetime and emitter injection ability or transistor gains. This critical time has been designated "inherent turn-off time," T_{Qi}, as it is a parameter, inherent in each thyristor, that predetermines the ability of the device to turn off quickly or not under normal operating conditions.

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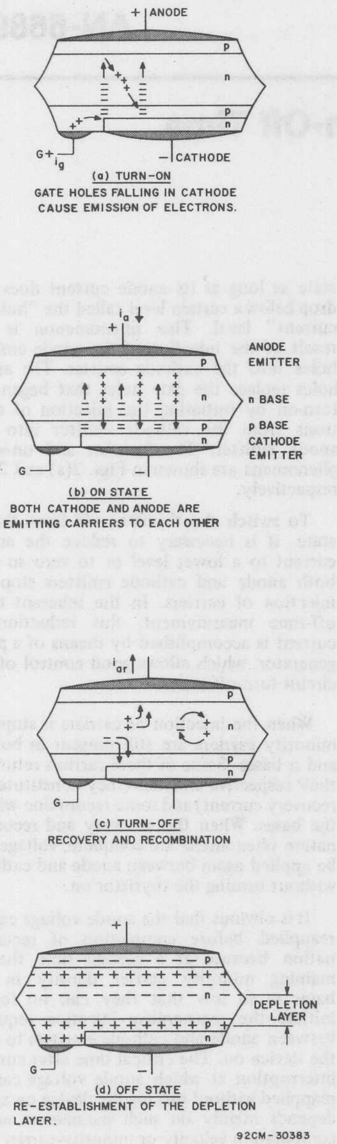


Fig. 2 — Turn-on and on-state phenomena.

INFLUENCE OF CIRCUIT VARIABLES ON DEVICE TURN-OFF TIME (T_q)

That turn-off time is a complex parameter depending on junction temperature, gate bias, and anode voltage and current waveforms is an unfortunate truth that can cause problems if one is not careful to analyze the influence of each variable separately. The following discussion is based on experiments and experience with fast-turn-off thyristors, SCR's and ITR's in television horizontal-deflection and regulator circuits and is therefore, not exhaustive. However, the operating conditions in the three main functions, trace, commutating, and direct-conducting regulator are so distinct and typical that they can be considered representative of many applications employing fast-turn-off thyristors.

Junction Temperature

As shown in Fig. 3, the turn-off time increases with temperature. This is true for all thyristors, but the degree of dependence varies from device to device, with gold-doped thyristors more sensitive to temperature than non-gold-doped types. This dependency is a prime limiting factor in practical designs. But it also represents an easy way for the circuit designer to artificially increase the thyristor turn-off time, and so to check the safety margin between circuit and thyristor turn-off times, as explained below.

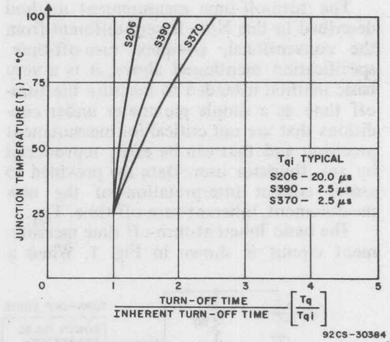


Fig. 3 — Turn-off time as a function of temperature.

Gate Bias

As shown in Fig. 4, reverse gate bias during turn-off is a circuit variable that influences thyristor turn-off time strongly, for two reasons. First, reverse gate bias during turn-off causes withdrawal of majority carriers from the p base; and second, reverse gate bias at the instant of and just after reapplication of the anode forward voltage creates a transverse field in the p base such that minority carriers remaining in the n base are partly directed out of the n emitter when the anode forward voltage is reapplied. Measured results with a short-duration reverse gate-bias pulse, Fig. 5, show that the optimum time to apply the bias for reducing turn-off is at reapplication of the anode voltage. Thus the first effect influences the turn-on time less than the second one.

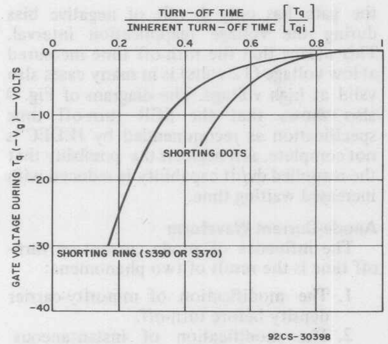


Fig. 4 — Influence on thyristor turn-off time of reverse gate bias during turn-off.

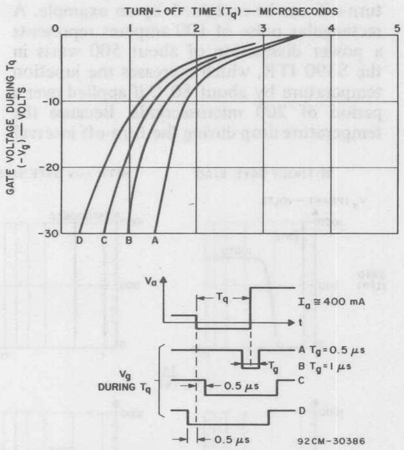


Fig. 5 — Measured results indicating that the optimum time to apply the bias for reducing turn-off is at reapplication of the anode voltage.

Experiments have shown that the reverse-gate bias influence on turn-off is less pronounced in thyristors in which the simple edge-shorting ring, as used in RCA deflection thyristors, has been replaced with cathode gate shorting dots. A comparison of technologies is given in Fig. 4. The significance of the figure is that a given turn-off time at zero gate bias will become a shorter turn-off time in devices employing the shorting ring in a circuit with reverse gate bias. Therefore, devices with basic gate-cathode design differences may not be compared without taking into account gate bias and circuit operating conditions.

The gate-bias influence on turn-off time is a feature that can be used by circuit designers to increase the operating frequency of a given thyristor; however, there are limitations. First is the dissipation within the p-base layer in the case of the thyristors with shorted gate-cathode construction. This dissipation can in some cases cause such an increase in junction temperature that the reduction in turn-off time becomes negligible. The second limitation is the gate-cathode avalanche breakdown, which can produce hot spots resulting in thermal turn-on of the thyristor.

Television horizontal-deflection trace thyristors are specially designed to accept reverse gate-to-cathode voltages of up to 35 volts, and so to allow circuit turn-off times in the order of 2 microseconds for switching off thyristors employed as deflection-circuit power switches.

Anode-Voltage Waveform

The influence of the anode-voltage waveform on thyristor turn-off time is relatively complex. Fig. 6 shows various waveforms

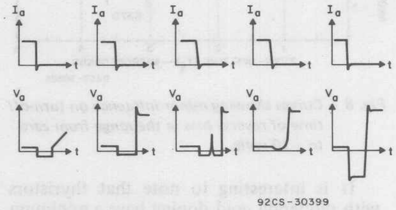


Fig. 6 — Some typical anode-voltage waveforms.

that may be encountered in practice. The anode-voltage waveform can be considered to consist of three separate parts:

- the anode voltage during the turn-off interval
- the reapplied dv/dt
- the reapplied peak voltage

The Anode Voltage During the Turn-Off Internal — In practice the thyristor may be operated with a reverse parallel diode or as a pure, controlled rectifier. When operating with the parallel diode, Fig. 7, the

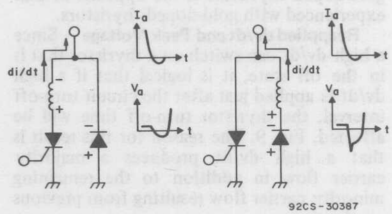


Fig. 7 — Thyristor operating with reverse parallel diode and as pure, controlled rectifier.

thyristor voltage during turn-off can vary from the amount of the diode drop, or a slightly reverse bias, to a slightly forward bias, following the stray inductances in series with the thyristor or diode. According to measurements made on gold-doped SCR's

and ITR's, Fig. 8, reverse bias in the range from zero to −10 volts has only minor influence on turn-off time.

If the anode voltage is not inverted during the turn-off interval, turn-off is not much affected, as long as the voltage is low enough to allow the anode current to drop below the holding current.

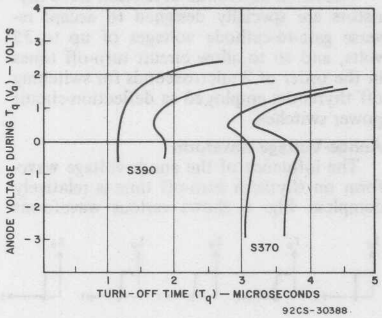


Fig. 8 – Curves showing minor influence on turn-off time of reverse bias in the range from zero to −10 volts.

It is interesting to note that thyristors with moderate gold doping have a minimum inherent turn-off time at anode voltages of approximately + 0.5 volt. Above + 1 volt, thyristor turn-off time increases rapidly as the anode current approaches the holding current during the turn-off interval.

The presence of higher negative anode voltages (in the order of 100 volts) during the turn-off interval and before reapplication of the positive anode voltage has an unfavorable effect on the turn-off time of gold doped thyristors, Fig. 9. However, these same voltages have a favorable effect on the peak voltage, dv/dt combination capability when the voltage is reapplied after a waiting time longer than the thyristor turn-off time.

The effect of reverse anode bias on non-gold-doped thyristors is the opposite of that experienced with gold-doped thyristors.

Reapplied dv/dt and Peak Voltage – Since a high dv/dt can switch on a thyristor that is in the off state, it is logical that if a high dv/dt is applied just after the circuit turn-off interval, the thyristor turn-off time will be affected, Fig. 9. The reason for this result is that a high dv/dt produces a majority carrier flow in addition to the remaining minority carrier flow resulting from previous conduction.

In the case of gold-doped thyristors, the gold has an additional effect in that it artificially increases the depletion layer and causes punch-through turn-on. This effect is more pronounced after long circuit turn-off times and at low junction temperatures.

The diagram of Fig. 9 shows that the turn-off time of some thyristors is not affected by dv/dt (below a limit level) when the gate has only 1 volt of negative bias during the voltage reapplication interval. This means that the turn-off time measured at low voltage (12 volts) is in many cases also valid at high voltage. The diagram of Fig. 9 also shows that the SCR turn-off time specification as recommended by JEDEC is not complete, as it neglects the possibility that the reapplied dv/dt capability is reduced with increased waiting time.

Anode-Current Waveform

The influence of anode current on turn-off time is the result of two phenomena:

1. The modification of minority-carrier density before turn-off.
2. The modification of instantaneous junction temperature during the turn-off interval (because of the power dissipation before turn-off).

The indirect influence of temperature on turn-off can be explained by an example. A rectangular pulse of 100 amperes represents a power dissipation of about 500 watts in the S390 ITR, which increases the junction temperature by about 50°C if applied over a period of 200 microseconds. Because the temperature drop during the turn-off interval

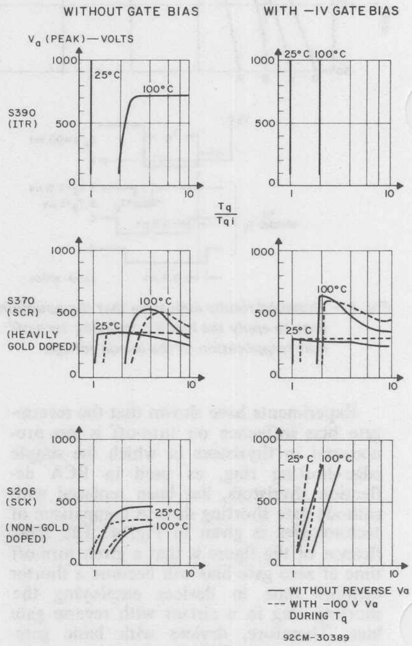


Fig. 9 – Diagrams indicating that the turn-off time of some thyristors is not affected by dv/dt (below a limit level) under certain conditions.

(approximately 10 microseconds) is negligible, the increase in turn-off time is approximately 50 percent. Fig. 10 gives the total

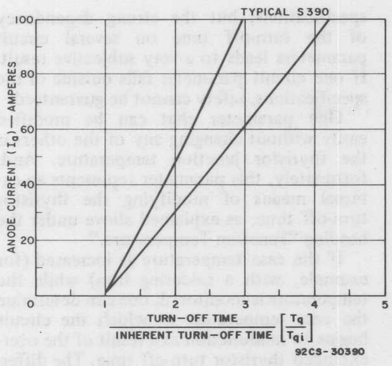


Fig. 10 – Total variation of Tq with anode current as measured with a current-pulse duration of 170 microseconds on S390 ITR's.

variation of T_q with anode current as measured with a current-pulse duration of 120 microseconds on S390 ITR's. Note that the peak current in TV applications never exceeds 15 amperes.

Because of its relatively weak influence on T_q, and as the current is generally closely limited by the application, this variable, anode-current waveform, can often be neglected.

TURN-OFF TIME MEASUREMENT CIRCUIT

The basic, practical, inherent turn-off time measurement circuit described above is very simple to set up; however, it can cause some problems if it is used as is because of the sensitivity of some thyristors to the anode/cathode bias during turn-off, and because of the necessity to adjust the generator pulse-width control for each device being measured. It also immobilizes an expensive pulse generator and an oscilloscope.

The inherent turn-off time measurement circuit shown and described in the appendix has been designed to overcome the above problems. It consists of a simple pulse generator whose pulse length is controlled automatically by feedback from a circuit that detects whether the thyristor under test is in the off-state or the on-state after the pulse action. By this means, the circuit turn-off pulse width automatically adapts itself to the thyristor turn-off capability. An additional integrator circuit has been added to provide a direct reading of the circuit turn-off pulse length on a panel micro-ammeter graduated in "inherent turn-off time." The design permits precise measurement of turn-off times between 1 and 200 microseconds, which is a sufficient range for measuring fast television-deflection-circuit thyristors (SCR's or ITR's) as well as most slow 50-Hz thyristor types (SCR's or triacs).

Inherent Turn-Off-Time Measurement Conditions

Anode-Current Amplitude and On-State Time – To minimize junction-temperature changes during the test, the current must be as low as possible. However, an on-state current too close to the holding current would permit some devices to turn-off by themselves or to tend toward turn-off, which would cause errors in circuit-commutated turn-off measurements. Therefore, the same anode conditions as used for I_{gt} measurement were chosen for the turn-off measurement, i.e., a 12-volt 30-ohm source. This choice allows the I_{gt} test to be done with the same turn-off test circuit.

The on-state time of 500 microseconds was chosen to assure the spread of conduction to the entire pellet area before the application of the circuit-commutation turn-off pulse.

Anode Voltage – The reapplied voltage of +12 volts was chosen to avoid danger to the operator, to reduce the power supply requirements, and to assure consistency with the I_{gt} test. This voltage also allows the application of a high instantaneous dv/dt without influencing the turn-off time.

The anode-to-cathode reverse voltage bias during turn-off was chosen to correlate with the applications in which a diode clamps the reverse bias, an important choice as shown by the curves of Fig. 8.

Anode Current, –di/dt and Voltage, dv/dt – Both anode current, –di/dt, and anode voltage, dv/dt, were chosen high enough so that the current fall time and voltage rise time are negligible compared to the measured turn-off time. The advantage of this arrangement is that the turn-off time can be specified as a pulse width (the width of the rectangular circuit-commutating pulse).

In ITR's, the dv/dt is far below the device capability; however, when the turn-off of sensitive-gate SCR's is being measured, even this low amplitude dv/dt can have an influence on the turn-off time. Therefore, the measurement on a device such as the S2060 must be interpreted with care, and eventually the dv/dt must be reduced by means of an external anode-to-cathode capacitor.

Temperature – A temperature of 25°C was chosen for simplicity, to avoid all of the problems associated with the use of a hot test, such as insertion time, temperature stabilization time, the need for a temperature control circuit, and a preheated hot plate.

The Automatic "Inherent Turn-Off Time" Measurement Circuit

The complete circuit diagram for the automatic "inherent turn-off time" measurement circuit is shown in the appendix. The principal elements of the circuit are a trigger generator that turns on the device under test repetitively, a variable-width rectangular-pulse generator that turns the device under test off by circuit commutation, and a

logic circuit that detects whether the device under test is on or off after the circuit commutation pulse.

The output of the on-off logic circuit determines whether the width of the pulse generated by the pulse generator will have to increase or decrease to adapt it to the turn-off capability of the device under test. The result is an automatic circuit-commutation pulse-width tracking capability that adapts itself to the turn-off of the device under test. A more detailed description of the circuit is given below.

The circuit uses three CD4001's as clock, variable pulse-width generator and logic function. The clock is adjusted to provide a square pulse with a 1-millisecond period. At the positive-going edge of the clock, a pulse is transmitted to the gate of the SCR under test to turn it on. At the negative going edge of the clock, a pulse is transmitted to the rf transistor T2, which takes over the current of the SCR under test to allow charge recombination within it.

The anode voltage is measured after this circuit turn-off pulse to detect whether the SCR under test is off or on. If it is on, the SCR under test did not turn-off, the output of the logic circuit is zero, and the integrator output voltage decreases slowly, which causes a slow increase of the circuit turn-off pulse width.

When the circuit turn-off pulse is long enough to allow the SCR under test to turn-off, the logic circuit output is positive, which results in a slowly decreasing circuit-turn-off pulse width.

The two diodes in the cathode circuit of the device under test polarize the device, anode to cathode, at about 0.5-volt reverse bias during turn-off. Potentiometer P3 compensates the differences in the polarization diodes in rf commutation transistor T2 and in antisaturation diode D1. The precise adjustment of P3 must be done as explained in the appendix.

The turn-off pulse width can be monitored on a scope, or integrated so that it can be read directly from a microammeter graduated in turn-off time. Five microseconds full scale was found to be the best for the S390, as actual total distribution ranges between 1 and 4 microseconds.

A laboratory circuit would be equipped with six full-scale turn-off time ranges of 5, 10,20,50,100 and 200 microseconds to permit the study of other non-gold-doped thyristors.

PRACTICAL USE OF THE INHERENT TURN-OFF MEASUREMENT

Determining Turn-Off Safety Margin

Generally, when a design is completed, the designer may be fully confident of its performance if all of the circuit waveforms fall within the thyristor manufacturer's data-sheet specifications. The turn-off safety margin can be determined approximately by comparing the circuit waveforms and the specifications, but the strong dependency of the turn-off time on several circuit parameters leads to a very subjective result. If one circuit parameter falls outside of the specifications, safety cannot be guaranteed.

One parameter that can be modified easily without changing any of the others is the thyristor junction temperature. And, fortunately, this parameter represents an external means of modifying the thyristor turn-off time, as explained above under the heading "Junction Temperature."

If the case temperature is increased (for example, with a soldering iron) while the temperature is monitored, one can determine the case temperature at which the circuit begins to malfunction as a result of the over-extended thyristor turn-off time. The difference between the maximum working case temperature and the above recorded temperature gives the turn-off safety margin when translated on the diagram of Fig. 3. The inherent turn-off time measurement circuit is helpful in separating out quickly the units of a thyristor sample lot with the longest turn-off times, Fig. 11, and so avoids the necessity of having to measure all of the samples, a precious time saving when designing a new circuit.

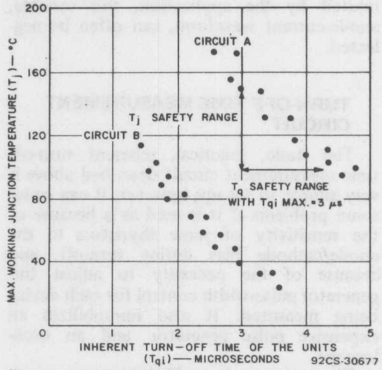


Fig. 11 – Inherent turn-off time of S390 units as a function of maximum working junction temperature in two typical circuits.

Determining Turn-Off Time Distribution Among Thyristors

The inherent turn-off time measurement is of interest to both device designers and production engineers as it permits them to quickly and economically determine turn-off time distribution diagrams on a routine basis, an impossibility with the methods normally used.

When designing a new circuit, it is very helpful to know the position in the distribution of turn-off of all of the thyristors employed. As more and more thyristors are used in high-frequency regulators and power circuits, mainly in the consumer-TV field, turn-off-time measurement becomes of greater importance to many people. Conventional turn-off measurement sets are, unfortunately, very expensive and, there-

fore, usually available only to thyristor manufacturers or large-volume circuit manufacturers who can justify the investment. The instrument described in this Note has a negligible cost compared to the information it can provide for design engineers.

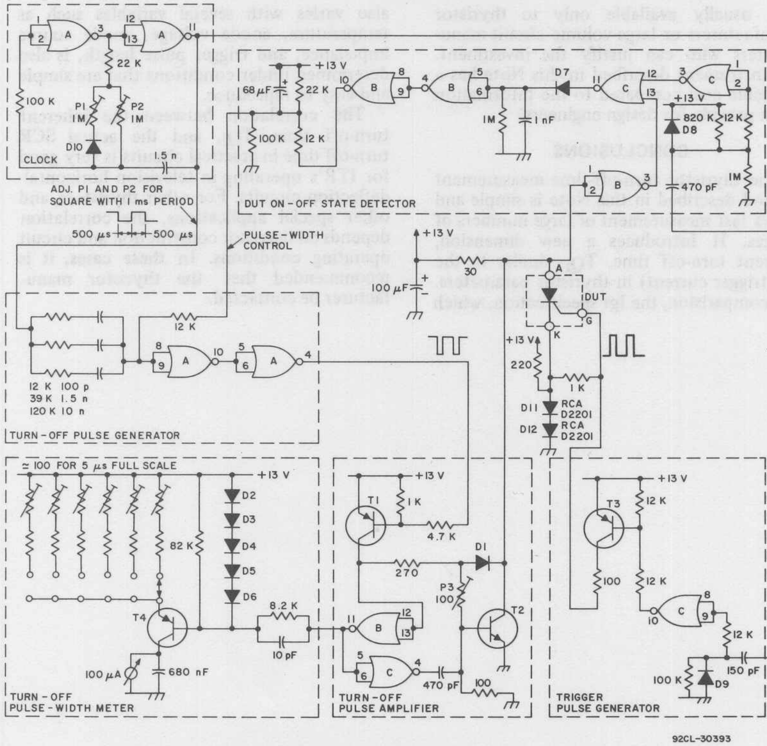
CONCLUSIONS

The thyristor turn-off-time measurement method described in this Note is simple and allows fast measurement of large numbers of devices. It introduces a new dimension, inherent turn-off time, T_{Qi}, similar to the Igt (trigger current) in thyristor parameters. For comparision, the Igt specification, which also varies with several variables such as temperature, anode voltage, anode source impedance, and trigger pulse length, is also determined under conditions that are simple and easy to reproduce.

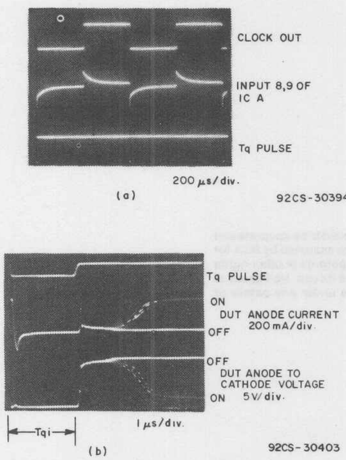
The correlation between the inherent turn-off time, T_{Qi}, and the actual SCR turn-off time in practical circuits is very good for ITR's operating in television horizontal-deflection circuits. For other thyristors, and other special applications, the correlation depends on thyristor construction and circuit operating conditions. In these cases, it is recommended that the thyristor manufacturer be contacted.

When incorporating RCA Solid State Devices in equipment, it is recommended that the designer refer to "Operating Considerations for RCA Solid State Devices", Form No. 1CE-402, available on request from RCA Solid State Division, Box 3200, Somerville, N. J. 08876.

APPENDIX – INHERENT TURN-OFF TIME MEASUREMENT CIRCUIT



Automatic Inherent-Turn-off-Time Measurement Circuit



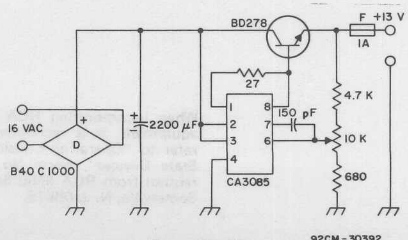
Measurement Circuit Waveforms

Adjustment Procedure

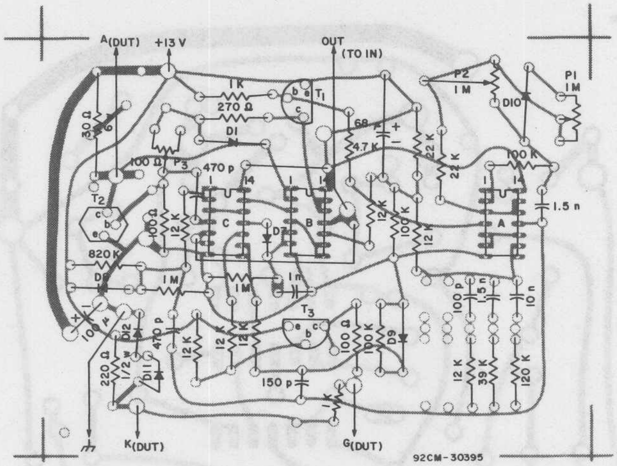
1. Coarse adjust supply at +13V.
2. Adjust clock (P1 and P2).
3. Fine adjust supply for DUT anode-to-cathode voltage of 12 volts.
4. Adjust P3 for minimum delay between pulse at output B11 and rise of DUT anode voltage. Adjustment is optimum when ringing just appears in the rise slope of the DUT anode voltage.
5. Adjust each scale resistor for coincidence of microammeter reading and scope T_{qi} reading.

Notes

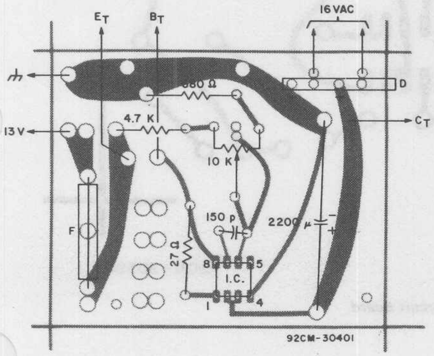
1. A,B,C, are RCA-CD4001; pin 7 to ground, pin 14 at +13V.
2. D1 through D10 are type 1N914 or 1N4148.
3. D11, D12 are D2201A.
4. T2 is type 2N5102 or 2N5070 (RF transistor).
5. T1, T3, T4 are BC557 or equivalent (p-n-p).



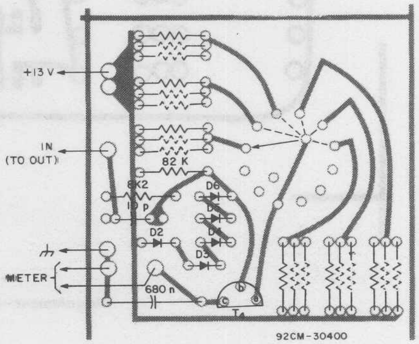
Power Supply



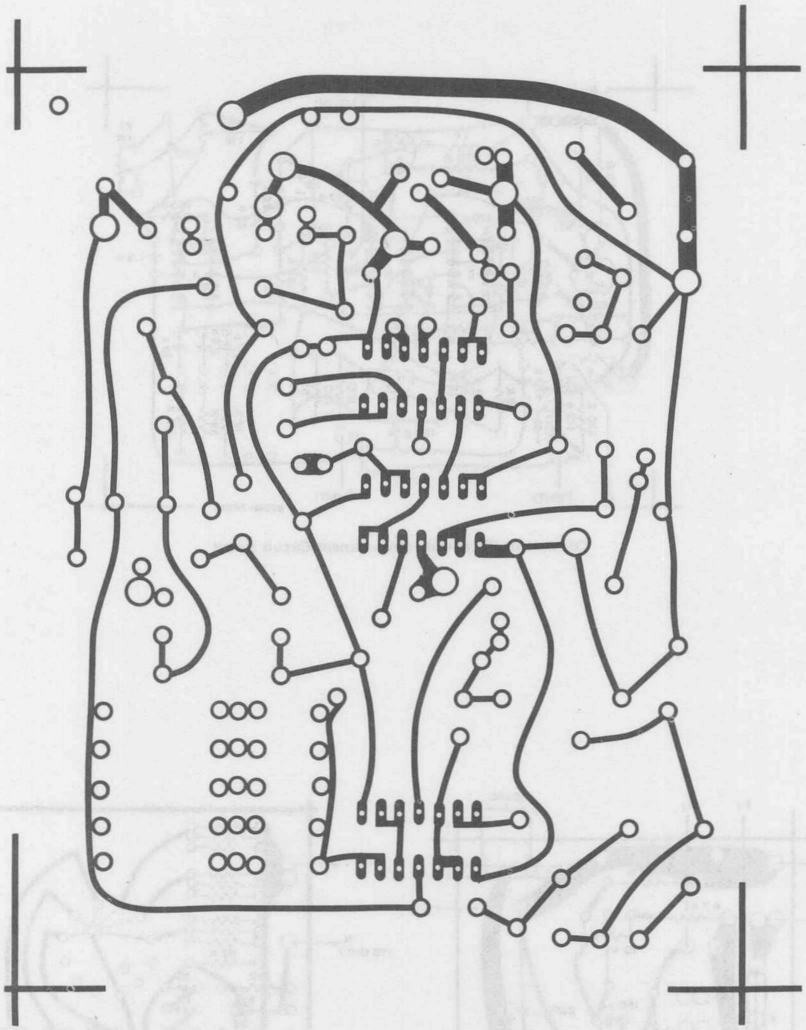
Component Placement—Measurement-Circuit Board



Component Placement—Power Supply



Component Placement—Turn-off Pulse Width Meter Board



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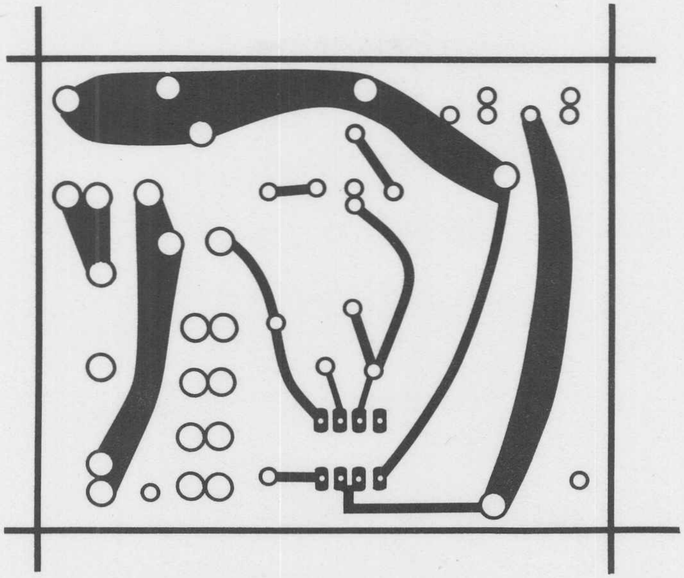
Measurement—Circuit Board



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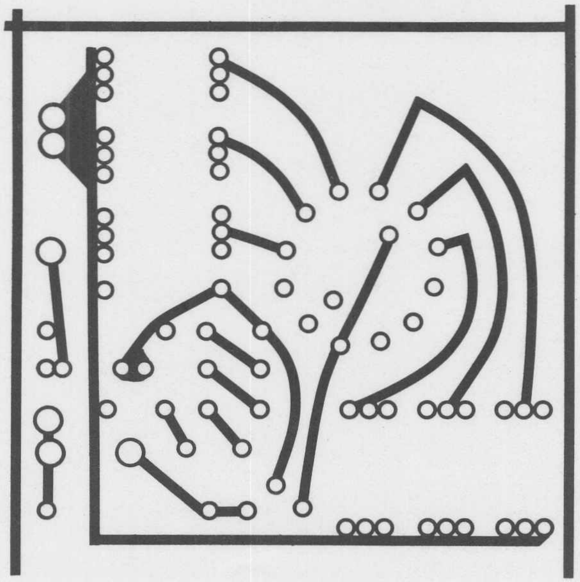
Power Supply Board



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Turn-off Pulse Width Meter Board

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